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APPLICATION

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TITLE: MOUNTING STRUCTURE FOR SUPERCONDUCTING WINDINGS

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MOUNTING STRUCTURE FOR SUPERCONDUCTING WINDINGS

RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Serial No. 09/481,480, filed January 11, 2000.

INCORPORATION BY REFERENCE

The following applications are hereby incorporated by referenced into the subject application as if set forth herein in full: (1) U.S. Application Serial No. 09/632,599, filed August 4, 2000, entitled "Superconducting Synchronous Machine Field Winding Protection" (Atty. Docket No. 05770-112001/ASC-458); (2) U.S. Application Serial No. 09/632,776 filed August 4, 2000, entitled "HTS Superconducting Rotating Machine" (Atty. Docket No. 05770-126001/ASC-450); (3) U.S. Application Serial No. 09/632,600, filed August 4, 2000, entitled "Exciter And Electronic Regulator For Superconducting Rotating Machines" (Atty. Docket No. 05770-121001/ASC-487); (4) U.S. Application Serial No. 09/632,601, filed August 4, 2000 entitled "Stator Support Assembly For Superconducting Rotating Machines" (Atty. Docket No. 05770-124001, 05770-122001/ASC-488, 491, and 493); and (5) U.S. Application Serial No. 09/632,602, filed August 4, 2000, entitled "Segmented Rotor Assembly For Superconducting Rotating Machines" (Atty. Docket No. 05770-123001/ASC-490).

The additional applications are also hereby incorporated by referenced into the subject application as if set forth herein in full: (1) U.S. Application Serial No. 09/480,430, filed January 11, 2000,. entitled "Exciter and Electronic Regulator for Rotating Machinery" (Atty. Docket No. 05770-101001/ASC-424); (2) U.S. Application Serial No. 09/480,397, filed January 11, 2000, entitled "Stator Construction for Superconducting Rotating Machines" (Atty. Docket No. 05770-102001/ASC-445; (3) U.S. Application Serial No. 09/481,483, filed January 11, 2000, entitled "Torque Transmission Assembly for Superconducting Rotating Machines" (Atty. Docket No. 05770-103001/ASC-446); (4) U.S. Application Serial No. 09/481,480, filed January 11, 2000, entitled "Internal Support for Superconducting Wires" (Atty. Docket No. 05770-105001/ASC-448); (5) U.S. Application

No. 09/481,484, filed January 11, 2000, entitled "HTS Superconducting Rotating Machine" (Atty. Docket No. 05770-106001/ASC-450); and (6) U.S. Serial No. 09/480,396, filed January 11, 2000, entitled "Cooling System for HTS Machines" (Atty. Docket No. 05770-108001/ASC-456).

TECHNICAL FIELD

This invention relates to the construction and operation of superconducting rotating machines, and more particularly to superconductor winding construction for use in superconducting motors.

BACKGROUND

Superconducting air core, synchronous electric machines have been under development since the early 1960s. The use of superconducting windings in these machines has resulted in a significant increase in the magnetomotive forces generated by the windings and increased flux densities in the machines. However, superconducting windings generate tremendous internal stresses that can result in a change in their physical shape. For example, the internal stresses generated within an operating racetrack shaped coil can cause its shape to become more circular. Because certain applications require the superconducting windings to be non-circular, the internal stresses must be addressed.

SUMMARY

The invention features a superconducting coil assembly of the type mounted to a rotor assembly of an electric rotating machine. The superconducting coil assembly, in operation, is maintained at cryogenic temperatures while the portion of the rotor assembly, to which it is mounted is maintained above cryogenic temperatures (e.g., close to room temperature).

In a general aspect of the invention, the superconducting coil assembly includes at least one superconducting winding wound about a longitudinal axis of the coil assembly and having an inner radial surface defining a bore extending through the coil assembly, and at least one support member extending across the bore and mechanically coupled to the portion of the rotor assembly and to opposing portions of the inner radial surface of the at least one superconducting winding.

Embodiments of this aspect of the invention may include one or more of the following features.

The portion of the rotor assembly mechanically coupled to the at least one support member has a concave surface while the support member includes a rounded member sized and shaped to be received with the concave surface of the portion of the rotor assembly. The at least one support member includes a broad planar surface in a plane substantially transverse to the at least one superconducting winding. The at least one support member is formed of a thermally insulative material (e.g., epoxy glass reinforced molding compound, such as G-10).

The superconducting windings are non-circular in shape, for example, a racetrack shape having a pair of opposing arcuate end sections and a pair of opposing substantially straight side sections. The at least one support member is mechanically coupled to the pair of opposing substantially straight side sections of the at least one superconducting winding. The at least one support member includes a broad planar surface in a plane substantially parallel with the at least one superconducting winding.

Among other advantages, the support member mechanically supports the cryogenically-cooled superconducting winding and transfers internal stresses generated by the windings to the rotor body. The support member is particularly advantageous for superconducting windings having a non-circular geometry. For example, with a racetrack-shaped coil having a pair of opposing arcuate end sections and a pair of opposing substantially straight side sections, the support member is mechanically coupled to the pair of opposing substantially straight side sections of the at least one superconducting winding. In such an embodiment, the support member effectively transfers the "ovalization" forces which cause the oval superconducting coils to become more circular.

Embodiments in which the support member has a concave surface and the support member includes a rounded member sized and shaped to be received with the concave surface of the portion of the rotor assembly has additional advantages. In particular, the rounded member serves to convert a portion of the tangential forces generated by the superconducting winding and conveyed through the support member to the rotor body into clamping forces. The clamping forces ensure a reliable mechanical connection between the support member and rotor body.

The at least one support member is formed of a thermally insulative material, such as an epoxy glass reinforced molding compound (e.g., G-10). In this way, the support member provides thermal isolation between the cryogenically-cooled superconducting windings and the "warm" (i.e., non-cryogenically-cooled) rotor body. Minimizing the heat loss in this way, increases the efficiency of the cooling system associated with cooling the windings, as well as the overall efficiency of the superconducting rotating machine.

In another general aspect of the invention, a support assembly for a superconducting coil assembly includes a support member having an outer wall surrounding the superconducting coil assembly; and a wedge having a first surface, attached to the outer wall of the support member.

In another aspect of the invention, a rotor assembly includes a rotor body; superconducting coil assemblies angularly spaced about the periphery of the rotor body; support members, as described above, and associated with a corresponding one of the superconducting coil assemblies; and wedges, each positioned between adjacent ones of the support members.

Embodiments of these aspects of the invention may include one or more of the following features. The wedges have a triangular shape. The superconducting coil assemblies include windings having superconductor and the support member is formed of a material (e.g., stainless steel) having a thermal expansion characteristic similar to or substantially the same as the superconductor. The support members include support plates extending from their outer walls, each support plate positioned between adjacent ones of the plurality of windings.

These and other features and advantages of the invention will be apparent from the following description of a presently preferred embodiment, and from the claims.

DESCRIPTION OF DRAWINGS

Fig. 1 is a cross-sectional perspective view of a superconducting motor in accordance with the invention.

Fig. 2 is a generic cross-sectional view of the superconducting motor of Fig. 1.

Fig. 3 is a perspective view of a stator assembly of the superconducting motor of Fig. 1.

Fig. 4 is a perspective view of a single phase of stator coils of the stator assembly of Fig. 3.

Fig. 5 is a perspective view of a single phase of stator coils mounted on the support tube of the stator assembly of Fig. 3.

Fig. 6 is a cross-sectional perspective view of a stator coil section of the stator assembly of Fig. 3.

Fig. 6A is a schematic of two stator coils and an associated cooling loop.

Fig. 7 is a cross-sectional perspective view of a rotor assembly of the superconducting motor of Fig. 1.

Fig. 8 is a cross-sectional perspective view of an output shaft and vacuum chamber of the rotor assembly of Fig. 7.

Fig. 9 is a perspective view of rotor coils mounted on a rotor body of the rotor assembly of Fig. 7.

Fig. 10 is a cross-sectional view of the rotor coil stack with internal support members of the rotor coils of Fig. 9.

Fig. 11 is a perspective view of an axial buckle of the rotor assembly of Fig. 7.

Fig. 12A is a perspective view of a tangential buckle of the rotor assembly of Fig. 7.

Fig. 12B is a perspective view of the tangential buckle of Fig. 12 mounted with a spring.

Fig. 13A is a cross-sectional perspective view of the tangential buckles mounted within the rotor assembly of Fig. 7.

Fig. 13B is a cross-sectional perspective view of the axial buckles mounted within the rotor assembly of Fig. 7.

Fig. 14 is a perspective view of a cryogenic cooling system and mounting flange of the superconducting motor of Fig. 1.

Fig. 15 is a block diagram of a cryogenic cooling system of the superconducting motor of Fig. 1.

Fig. 16 is a cross-sectional end view of a portion of another embodiment of a rotor coil support assembly having a horizontal support plate.

Fig. 17 is a top view of the rotor assembly of Fig. 16 with the pole cap removed.

Fig. 18 is a diagrammatic perspective view, partially in cross section, of the rotor coil support assembly having vertical support plates.

Fig. 18A is an exploded view of a portion of the rotor coil support assembly along line 18A-18A.

Fig. 19 is a cross-sectional end view of the rotor coil support assembly .

Fig. 20 is a cross-sectional top view of the rotor assembly of Fig.18.

Fig. 21 is a cross-sectional top view of a portion of the rotor assembly shown in Fig. 20.

Fig. 22 is a diagrammatic representation of the forces associated with the portion of the rotor assembly of Fig. 21.

Fig. 23 is a cross-sectional end view of a portion of another embodiment of a four-pole rotor assembly for a superconducting motor having support wedges.

Figs. 24A and 24B are cross-sectional end views of portions of the four-pole rotor assembly of Fig. 23

Fig. 25 is an embodiment of an eight-pole rotor assembly for a superconducting motor.

Fig. 26 shows a portion of an air-core embodiment of a support wedge structure.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Referring to Fig. 1 and 2, a superconducting synchronous motor 10 includes a rotor assembly 50 cooled by a cryogenic cooling system 100, here a Gifford McMahon (GM) cooling system, and surrounded by a stator assembly 20. Both the stator assembly 20 and the rotor assembly 50 are mounted in a housing 12 to protect the components and any users of the superconducting motor 10. As will be described in greater detail below, each of these components and assemblies have features which contribute toward both increasing the overall performance, as well as reducing the overall size of motor 10. In particular, superconducting synchronous motor 10 can be shown to produce torque densities as high as 150 N m/Kg or more at 300 RPM or less. Furthermore, such motors are expected to provide a greatly improved gap shear stress characteristic in a range between 30 psi and 100 psi.

Referring to Fig. 1 and 3-5, the stator assembly 20 includes, in this embodiment, one hundred eight stator coils 22 wound around a support tube 34, and arranged in a multi-phase configuration, here a 9-phase configuration. The twelve stator coils 22 per phase provide a 12-pole arrangement. A back iron 36 is constructed by wrapping magnetic wire around the stator coils 22. The stator coils 22 are wound into a diamond pattern, with one stator coil 22 diamond representing a single pole. The stator coils 22 are arranged around the support tube 34 by overlapping sides of adjoining stator coils 22 in the same phase.

Referring to Fig. 6, cooling conduits 30 are positioned to be in thermal contact with each stator coil 22 to facilitate cooling of the stator assembly 20. Each cooling conduit 30 is constructed from a thin walled, high electrical resistivity alloy for minimizing eddy current heating. Each coolant passage of the cooling conduit 30 is distinct and electrically isolated from the adjacent coolant passage. Because the cooling conduits 30 are generally constructed from an electrically conductive material, an electrically insulating tape 28 is wrapped about the stator coil 22 to electrically insulate the stator coil 22 from surrounding components that are at ground potential, particularly the cooling conduits 30. In particular, the electrically insulating tape 28 maintains the cooling conduits 30 at ground potential, thereby permitting the use of fresh water, which contains ions. The electrically insulating tape 28 is made from a material having a thickness that can withstand operating voltages of the conductor turns 24, as well as the heat generated by the conductor turns 24. The thickness of the electrically insulating tape 28 is determined by the dielectric strength (insulating properties) of the material and operating voltage, typically between about 0.001 to 0.100 inches. Examples of materials for the electrically insulating tape 28 include, but are not limited to, epoxy, mica, and glass tapes.

In this embodiment, the stator coils 22 are formed of an array of multiple conductor turns 24. Each conductor turn 24 is electrically isolated from an adjacent turn by insulation 26. Insulation 26 may be formed of the same material as electrically insulating tape 28, but has a reduced thickness (e.g., 0.001 to 0.030 inches).

Referring to Figs. 6 and 6A, cooling conduits 30 are mounted adjacent to and in contact with the electrically insulating tape 28 surrounding each stator coil 22. Each cooling conduit 30 has a number of passages extending therethrough for receiving a coolant from a fresh water external source 200. With reference to Fig. 3, each cooling conduit 30 has an

opening (not shown) at the end regions of each stator coil 22. Therefore, one hundred eight openings are in fluid communication with a manifold assembly (not shown) to allow fluid into each cooling conduit 30 from the external source 200. On the other side of the stator coils 22, one hundred eight openings are in fluid communication with a return 202. In one embodiment, the manifolds are end caps (not shown) circumferentially mounted to the front and back edge of the stator assembly 20.

A porous copper thermally conductive member 32, which has low eddy current generation, is disposed about the stator coil 22 and cooling conduits 30 to facilitate cooling of the entire stator coil 22. In other embodiments, this could be constructed from a wire disposed about the stator coil 22. Absent the thermally conductive member 32, the stator coil 22 would only be cooled at the contact point between the cooling conduit 30 and the electrically insulating tape 28. Because of this contact point cooling, a thermal gradient would be induced through the electrically insulating material 28. This thermal gradient creates thermal stresses between the cooling conduit 30 and the electrically insulating tape 28, which can cause premature failure in the stator assembly 20 due to electrical breakdown at this interface. Additionally, with high power density embodiments, the cooling conduit 30 cannot be mounted on a wide side of the stator coil 22 due to the required high packing densities. To minimize the peak temperature, the thermally conductive member 32 is positioned around the stator coil 22 and the cooling conduit 30 to allow heat transfer from the sides of the stator coil 22 that are not in direct contact with the cooling conduit 30.

In certain embodiments, cooling of the stator assembly 20 is further enhanced by varying the thickness of the electrically insulating material 28. The electrically insulating material 28 isolating the conductor turns 24 in each diamond-shaped stator coil 22 from the grounded thermally conductive member 32 experiences varying dielectric stress dependent on the electrical location of the coil within a given phase of the stator assembly 20 with stator coils 22 connected in series. The two stator coils 22 at the end of the phase are connected directly to line voltage and their electrically insulating material 28 experiences maximum dielectric stress between conductor turn 24 and the thermally conducting member 32. The coils electrically located midway between the ends of the phase are exposed to approximately half the dielectric stress due to the voltage drops in the stator coils 22 between the end and middle of the phase. The thickness of the electrically insulating material 28 is varied in

uniform steps directly proportional to the voltage variation. In one embodiment, the minimum thickness of the electrically insulating material 28 thickness is calculated by the relationship $T_{ins}*(0.5 + (1/N))$, where T_{ins} represents the maximum thickness of the electrically insulating material 28 at coils connected to the line voltage and N represents the even number of stator coils 22 in each phase. The electrically insulating material 28 thickness will proportionally vary in uniform steps between the maximum thickness, T_{ins}, and the minimum thickness. Varying the thickness of the electrically insulating material 28 will help facilitate cooling, since thicker electrically insulating material 28 will not be used where it is not needed.

In another embodiment, the stator coils 22 in each phase may be arranged and connected in pairs in a two layer winding with stator coils 22 having the thinnest and thickest electrically insulating material 28 being paired. Stator coils 22 with the next thinnest and next thickest electrically insulating material 28 are then paired, this process being continued until the final two middle stator coils 22 are paired.

In certain other embodiments, the benefits of varying the thickness of the electrically insulating material 28 can be enhanced by varying the cross sectional area of each of the two stator coils 22 in the above described pairs of stator coils 22. The cross sectional area of the conducting turns 24 in the stator coil 22 with thin electrically insulating material can be decreased as higher power can be dissipated due to the decreased thermal resistance of the thin electrically insulating material 28. This makes room in the same coil pair to decrease the power dissipation in the remaining coil with thick electrically insulating material 28 by increasing the cross sectional area of its conducting turns 24. Typically winding temperature rise is reduced by 30 percent compared with the result of using conventional art with uniform insulation thickness and uniform wire cross sectional areas. Increased resistance to voltage breakdown between the conducting turns 24 and the adjacent thermally conductive member 32 can be obtained compared with conventional art by increasing the thickness of electrically insulating material 28 on each of the coils in the above coil pairs for the same higher temperature as obtained with conventional art.

Referring to Fig. 7, the rotor assembly 50 includes a rotor body 58, onto which the superconducting rotor coils 52 are fixed, mounted onto an output shaft 82 by an array of tangential buckles 70 and axial buckles 60. As will be explained in detail below, the

tangential buckles 70 and the axial buckles 60 transfer the torque and forces produced by the rotor coils 52 to the output shaft 82, while also thermally isolating the cryogenically cooled rotor body 58 from the output shaft 82. The tangential buckles 70 and axial buckles 60 are mounted between rotor body ribs 59 and output shaft plates 84, as will be described in detail below. Vacuum chamber walls 86 are integrally mounted to the output shaft 82, enclosing. the rotor assembly 50 and acting as a cryostat. As will be described in detail below, a closed cryogenic cooling loop 118 (Shown in Fig. 2) is used to conduct heat from the rotor coils 52 to the cryocooler 104 where the heat can be dissipated. In particular embodiments, vacuum chamber 86 includes an outer cylindrical wall that, for reasons discussed below, serves as an electromagnetic shield 88.

Referring to Figs. 7 and 8, the output shaft 82 includes multiple plates 84 extending radially outward from the output shaft 82 surface. The multiple plates 84 include a first set of circumferentially extending plates 84A positioned around the output shaft 82 and a second set of longitudinally extending plates 84B positioned along the output shaft 82. Walls of the plates 84 form generally rectangular pockets, here thirty in number, around the surface of the output shaft 82 into which the tangential buckles 70 and axial buckles 60 mount. The plates 84 also include radial slots. Specifically, longitudinal plates 84B include radial slots 85B in every rectangular pocket wall around the output shaft 82 formed by the longitudinal plates 84B for mounting the tangential buckles 70. Similarly, the circumferential plates 84A define radial slots 85A in every other rectangular pocket wall around the output shaft 82 formed by the circumferential plates 84A for mounting the axial buckles 60. However, the present embodiment only utilizes three axial buckles displaced within the rectangular pockets in the middle of the rectangular pocket array. That is, no radial slots 85A are found on the outer circumferential plates 84A.

Referring again to Fig. 2, as discussed above, a vacuum chamber 86 is integrally mounted to the output shaft 82 and encloses the rotor assembly 50. The vacuum chamber 86 also encloses the circumferential plates 84A and longitudinal plates 84B, and is sized to allow the rotor body 58 and rotor coils 52 to be mounted to the output shaft 82. The output shaft 82 extends beyond the vacuum chamber 86 and the plates 84 at both ends. On one end, the output shaft 82 extends to connect to an external load that the motor 10 will drive. At the other end, the output shaft 82 connects to a rotating half of a brushless exciter 16.

The brushless exciter, shown in Figure 2, includes a rotating disk 16 spaced from a stationary disk 14 (e.g., spaced 1-4 mm). Rotating disk 16 is formed of a high permeability laminated material (e.g., iron) and includes a pair of concentric grooves within which a pair of coil windings is disposed. Stationary disk 14 is similarly formed of a high permeability material and includes a pair of concentric grooves within which a pair of coil windings is disposed. In essence, this arrangement provides a transformer having a primary, which rotates relative to a secondary of the transformer (or vice versa). An important feature of this particular arrangement is that the flux linkage generated by stationary disk 14 and rotating disk 16 when stationary is the same as when the rotating disk rotates. This feature advantageously allows superconducting rotor coils 52 to be charged prior to rotating disk 16 rotating (i.e., before motor 10 operates). The structure and operation of the brushless exciter is described in U.S. Patent Application Serial No. 09/480,430, entitled "Exciter and Electronic Regulator for Rotating Machinery," filed on January 11, 2000, and assigned to American Superconductor Corporation, assignee of the present invention.

The rotor assembly includes an electromagnetic shield 88 wrapped around the vacuum chamber 86, formed preferably from a non-magnetic material (e.g., aluminum, copper). In embodiments in which vacuum chamber 86 is formed of a different material, such as stainless steel, electromagnetic shield 88 can be mechanically located around the outer wall of the vacuum chamber 86. Electromagnetic shield 88 also acts as an induction structure (i.e., supports induction currents) and is, therefore, multi-purposed. Specifically, electromagnetic shield 88 intercepts AC magnetic fields from the stator before they impact the superconducting windings 26 of the rotor assembly 12. Further, because electromagnetic shield 60 acts as an induction structure, it can be used to operate the synchronous superconducting motor 10 at start-up in an induction mode. The electromagnetic shield 88 allows the superconducting motor 10 to operate as an induction motor for start up or in a continuous mode as a backup mode in case of a catastrophic failure of the cryogenic systems. This mode of operating a synchronous motor is described in U.S. Patent Application Serial No. 09/371,692, assigned to American Superconductor Corporation, assignee of the present invention, and is incorporated herein by reference.

Referring to Fig. 9, the rotor assembly 50 further includes superconducting rotor coils 52 mounted to a stainless steel rotor body 58 for support. The rotor body 58 also carries the

closed cryogenic cooling loop 118 (Fig. 15) that cools the rotor coils 52. The rotor body 58 is tubular with an inner surface 90 and an outer surface 92. The outer surface 92 may be generally cylindrical in shape, or may have flats machined to accept the rotor coils 52. The machined flats may, for example, give the outer surface 92 a general pentagonal, hexagonal or heptagonal shape. In the present invention, twelve flats have been machined to accept twelve flat rotor coils 52.

The rotor body 58 includes rotor body ribs 59 to mount the tangential buckles 70 and axial buckles 60, which interface with the output shaft 82. The rotor body ribs 59 are circumferentially fixed on the inner surface 90 and extend radially inward from the inner surface 90 of the rotor body 58.

In this embodiment, the superconductor in the rotor coils 52 is a high temperature copper oxide ceramic superconducting material, such as $Bi_2Sr_2Ca_2Cu_3O_x$ or $(BiPb)_2$, commonly designated BSCCO 2223 or BSCCO (2.1)223. Other high temperature superconductors including YBCO (or superconductors where a rare earth element is substituted for the yttrium), TBCCO (i.e., thallium-barium-calcium-copper-oxide family), and HgBCCO (i.e., mercury-barium-calcium-copper-oxide family) are also within the scope of the invention. Rotor coils 52 may be formed with pancake coils either single or double layers. In certain embodiments, double pancake coils with the two coils of a pair being wound from the same continuous length of superconducting tape may be used. In this case, a pancake coil may include a diameter smaller than its associated pancake coil of the double pancake. An approach for using this approach is described in U.S. Patent 5,581,220, which is assigned to American Superconductor, the assignee of the present invention, and incorporated herein by reference. Preferred embodiments are based on the magnetic and thermal properties of high temperature superconducting composites, preferably including superconducting ceramic oxides and most preferably those of the copper oxide family. The structure and operation of the superconducting windings is described in U.S. Patent Application Serial No. 09/415,626, entitled "Superconducting Rotating Machine," filed on October 12, 1999, assigned to American Superconductor Corporation, assignee of the present invention, and incorporated herein by reference.

Referring to Fig. 10, the rotor coils 52, as described above, are fabricated with an internal support 54 to help stabilize the structure because the racetrack configuration

produces tremendous bending stresses that attempt to push the superconducting coil assembly apart. To overcome this limitation, the rotor coils 52 are fabricated in a laminated configuration with internal coil supports 54, alternating between superconducting windings 126 and internal support 54. External supports, such as the inner spacer 140 and the outer spacer 142, do not sufficiently alleviate the internal stresses associated with non-circular and non-linear configurations, such as the racetrack configuration. The addition of internal coil supports 54 combined with the inner spacer 140 and outer spacer 142 gives mechanical strength to the rotor coil 52 and reduces the internal strains in the superconducting coils 126. The internal strains are reduced by using the internal coil supports 54 partly because the peak strains are located at the inside diameter of the superconducting coils 126, far removed from any external support structures that could be employed.

In the present embodiment, the internal coil support 54 is 40-mil thick stainless steel. However, it can be appreciated that various thicknesses and materials (such as copper or fiberglass composites) would work for their intended purposes, as various embodiments would require different thicknesses to optimize performance. In certain embodiments, a thermally conductive coating can be applied to the internal coil support 54 to provide better heat conductivity to cryogenic cooling tubes 118 located within the rotor body 58. For example, the internal coil support can be coated with copper.

A fastener can be used to tie the internal coil supports 54 together. For example, the layers can be mechanically fastened together by passing a bolt, or multiple bolts, through the internal coil supports 54 at a point within the annular opening 136 created by the superconductor windings 126 and fixing the assembly and top cap 144 to the rotor body 58. The bolts tie the internal coil supports 54 together into a unitary whole, resulting in even greater mechanical strength. The rotor coils 52 can also be epoxied together, with or without fasteners, to further fix the lamination together.

The internal coil support member 54 will also have various openings (not shown) to facilitate electrical connections between adjacent superconductor windings. Each superconducting coil assembly in the rotor coils 52 has to be electrically connected. Since the internal support members 54 are placed between each rotor coil 52, an opening must be provided to allow the electrical connection between each rotor coil 52.

Referring to Figs. 11 and 13B, the axial buckles 60 are assembled in the rotor assembly 50 to prevent axial movement between the rotor body 58 and the output shaft 82. The axial buckles 60 also thermally isolate the cryogenically cooled rotor body 58 from the output shaft 82 by using a thermally isolating coupling band 66 between the coupling members 62 and 64.

A generally U-shaped coupling member 62 is mounted to the rotor body 58 by sliding the open end over the rotor body rib 59. The rotor body rib 59 constrains the U-shaped coupling member 62 in the axial direction. Two smaller coupling members 64 are mounted in opposing radial slots 85A in the circumferential output shaft plates 84A by a narrow shoulder 65 on one face of the smaller coupling members 64. The narrow shoulder 65 slides into the radial slot 85A while the rest of the smaller coupling member 64 is wider than the radial slot 85A, thereby preventing the smaller coupling member 64 from moving beyond the slot 85A. The two smaller coupling members 64 are mechanically coupled to the U-shaped coupling member 62 by thermally isolating coupling bands 66. The thermally isolating coupling bands 66 are Para-aramid/Epoxy straps. By using thermally isolating coupling bands 66, the output shaft 82 and the rotor body 58 are thermally isolated from each other since the coupling bands 66 are the only direct connection between the U-shaped coupling member 62 and the smaller coupling members 64. This thermal isolation helps prevent the output shaft 82 from acting as a heat sink.

The coupling bands 66 wrap around spherical ball end couplings 69 mounted in the U-shaped coupling member 62 and the smaller coupling members 64. The spherical ball end coupling 69 in one of the smaller coupling members is a cam 68, which is used to preload the coupling bands 66. Surrounding the cylindrical pins 72 and cam 68 are spherical ball ends 69. The spherical ball end couplings 69 hold the coupling band 66 and provide misalignment take-up. The spherical ball end couplings 69 maintain even loading to the coupling band 66. The coupling bands 66 are preloaded by turning the cam 68 to vary the tension. The coupling bands 66 are 180° apart, which allows one cam to tension both coupling bands 66 at the same time and put both coupling bands 66 in uniaxial tension. This configuration also constrains the rotor body 58 and output shaft 82 in both axial directions. The adjustability of the cam 68 allows each axial buckle 60 to be quickly preloaded by adjusting to any

manufacturing tolerance differentiation within the coupling bands 66, thereby facilitating a quicker build time for the rotor assembly 50.

Referring to Figures 12A and 13A, the tangential buckles 70 are assembled in the rotor assembly 50 to transfer the rotational forces between the rotor body 58 and the output shaft 82. The tangential buckles 70 also thermally isolate the cryogenically cooled rotor body 58 from the output shaft 82 by using a thermally isolating coupling band 66 between the coupling members 72 and 74.

An X-shaped coupling member 74 is mounted to the output shaft 82 by two recessed slide mounting areas 78 located on opposing legs of the X-shaped coupling member 74. These recessed slide mount areas 78 are positioned such that the X-shaped coupling member 74 mounts parallel to the axis of the output shaft 82. The recessed slide mounting areas 78 slide down into the radial slot 85B in the longitudinal plates 84B, which constrain the X-shaped coupling 74 in the circumferential and axial directions. Two spherical ball end coupling 69 are mounted between the rotor body ribs 59 by pressing a cylindrical pin 72 through the rotor body ribs 59 and a spherical ball end coupling 69. The spherical ball end couplings 69 are mechanically coupled to the X-shaped coupling member 74 by thermally isolating coupling bands 66. As discussed above, the thermally isolating coupling bands are Para-aramid/Epoxy straps, which thermally isolate the rotor body 58 from the output shaft 82.

Referring to Figs. 12A and 12B, the coupling bands 66 wrap around spherical ball end couplings 69 mounted in the X-shaped coupling member 74, in the two legs not defining the recessed slide mounting area 78, and around the spherical ball end coupling 69 mounted in the rotor body ribs 59. The coupling bands 66 are mounted 180° apart, which allows both coupling bands to be in uniaxial tension. The X-shaped coupling member 74 defines an opening 80 therethrough sized to accept a spring 96, which preloads both bands in uniaxial tension. The opening 80 is defined so as to be perpendicular to the axis of the output shaft 82 when the X-shaped coupling member 74 is mounted to the output shaft 82, allowing the spring 96 to push the X-shaped coupling member 74 radially outward. The spring 96 allows the tangential buckle 70 to be preloaded by compressing the spring 96. The spring 96 also allows for some compliance when the tangential buckle 70 is assembled within the rotor assembly 50. The compressed spring 96 allows each tangential buckle 70 to be quickly

preloaded by adjusting to any manufacturing tolerance differentiation within the coupling bands 66, thereby facilitating a quicker build time for the rotor assembly 50. The preload feature also facilitates loading the coupling bands 66 in pure tension. By loading the coupling bands 66 in pure tension, the assembly can transmit an extremely large torque between the rotor body 58 and the output shaft 82.

The longitudinal output shaft plates 84B are sized within axial slots (not shown) in the rotor body 58 such that they will bottom out during a high fault loading situation, thereby preventing the coupling bands 66 from breaking. If a sudden shock load is applied to the motor 10, metal-to-metal contact will occur. The advantage to designing such a shock system is that the coupling bands 66 do not have to be sized for fault and shock loads, which would make the coupling bands 66 impractical.

Referring to Figures 2, 14 and 15, a cryogenic cooling system 100 is used to maintain a cryogenic fluid at cryogenic temperatures and move the cryogenic fluid to and from a cryogenic cooling loop 118 located adjacent and in thermal communication with the rotor coils 52. The cryogenic fluid is moved through the cryogenic cooling loop 118 by a cryogenically adaptable fan 114. This system helps maintain the rotor coils 52 at cryogenic temperatures, because the superconducting rotor coils 52 have to be maintained at cryogenic temperatures (i.e., below –79°C) to operate properly and efficiently. The cryogenic cooling system 100 includes multiple cryogenically cooled surfaces 102, here Gifford-McMahon cold heads, mounted in cryocooler assemblies 104, a mounting flange 106 and a cryogenically adaptable fan 114. The cryogenic cooling system 100 utilizes a closed loop system for efficiency and ease of maintenance.

The advantage of more than one cryogenically cooled surface 102 is efficiency and ease of maintenance. First, more than one cryogenically cooled surface 102 in series will allow each cryogenically cooled surface 102 to work less to lower the temperature of the cryogenic fluid. Also, if one cryogenically cooled surfaces 102 malfunctions, the redundancy in the system will be able to overcome the loss. Further, if one cryogenically cooled surface 102 does malfunction, the malfunctioning cryogenically cooled surface 102 can be isolated from the system by proper valving, and maintenance performed without shutting down the system or introducing contaminants into the system.

The cryocooler assembly 104 mounts to the outside of the superconducting motor 10 via a mounting flange 106 fixed to the housing 12. The fixed cryocooler assembly 104 is in fluidic communication with a cryogenic cooling loop 118. In an embodiment with a rotating thermal load, such as the rotor coils 52, the cryocooler assembly 104 interfaces with the rotating cryogenic cooling loop 118 by interfacing with a rotary seal 108, here a ferrofluidic rotary seal. The rotary seal 108 allows the cryocooler assembly 104 to remain fixed while the cryogenic cooling loop 118 rotates with the rotor assembly 50. The cryocooler assembly 104 is maintained stationary, rather than rotating, due to undesirable high gravity heat transfer seen internal to the cryocooler assembly 104 if it were to rotate. The cryogenic cooling loop 118 is in thermal communication with the rotor coils 52, maintaining the rotor coils 52 at a cryogenic temperature.

The cryocooler assembly 104 is open to the vacuum chamber 86 of the rotor assembly 50. Keeping the internal area of the cryocooler assembly 104 at vacuum helps to isolate the portion of the cryogenic cooling loop 118 that is located within the cryocooler assembly 104 from outside temperatures. The vacuum isolation further helps improve the efficiency of the cryogenically cooled surfaces 102.

The cryogenic fluid, helium in this embodiment, is introduced into the system from a cryogenic fluid source 116. The cryogenic cooling system is a closed system, but cryogenic fluid will have to be added periodically should any leaks develop. Other cryogenic fluids, such as hydrogen, neon or oxygen, may also be used.

The cryogenic fluid must be moved from the cryocooler 104 to the portion of the cryogenic cooling loop 118 located within the rotor body 58. A cryogenically adaptable fan 114 is employed to physically move the cryogenic fluid. The advantage of a fan is that a fan does not require a heat exchanger to warm the fluid to the temperature of an ambient compressor, is inexpensive and is relatively small. In comparison, a prior art room temperature compressor in conjunction with a heat exchanger is more expensive and is much larger. Further details of the operation of the cryogenic cooling system 100 can be found in U.S. Patent Application Serial No. 09/480,396, entitled "Cooling System for HTS Machines," filed on January 11, 2000, and assigned to American Superconductor Corporation, assignee of the present invention.

As was described above in conjunction with Fig. 10, rotor coils 52 were constructed in a laminated arrangement and included internal supports 54 to alleviate bending stresses generated by the superconducting windings 126 and increase the overall mechanical strength of the coil assembly. In this embodiment, the rotor coils 52 were mounted directly on the cryogenically-cooled rotor body 58. In other embodiments, however, the rotor body is not cooled. Thus, supporting the rotor coils 52 on the rotor body 58 while maintaining thermal isolation between these components is an important consideration.

For example, referring to Figs 16 and 17, in another embodiment, a support plate 302 is incorporated within a rotor coil assembly 304 formed of a stacked, laminated arrangement of superconducting windings 306 and internal supports 308. Support plate 302 serves to mechanically support the rotor coils relative to a mounting pedestal 309 of the warm rotor body. To ensure adequate thermal isolation between the cryogenically-cooled rotor coils and warm rotor body, support plate 302 is formed of a rigid and thermally insulative material, such as G10, a woven-glass material commonly used for fabricating printed circuit boards. The thickness of support plate 302 is in the range of about 2 mm and 4 mm and is generally a function of the rating (e.g., 25 Mwatt, 120 rpm, 12 pole) and application of the rotating machine.

As was the case in the embodiment of Fig. 10, an inner spacer 310 and an outer spacer 312 are used to externally support the superconducting windings. Internal supports, inner spacer, and outer spacer are formed of a relatively rigid and, unlike support plate 302 is typically formed of a thermally conductive material, such as stainless steel. Once again, the material and thickness of the internal supports and spacers depend primarily on the torque and particular application of the machine.

A number of support blocks 313 are spaced along a top surface of the rotor coil 52 and positioned between the rotor coil assembly and a top or pole cap 320. Rotor coil assembly 304 includes support poles 314a on the upper surface of the laminated arrangement of windings 306 to distribute the load between support blocks 313 and the superconducting windings. Similarly, support plates 314b are positioned between a bottom surface of the laminated arrangement of superconducting windings 306 and rotor assembly. Support plates 314a, 314b are formed of a relatively rigid and high strength material such as stainless steel. Support blocks 313 provide a relatively lightweight, cellular structure made from either

metallic sheet materials or non-metallic materials (e.g., resin-impregnated paper or woven fabric), such as those materials commercially available from Hexcel Corporation, Duxford, UK. For example, one structural fabric well-suited for use as a support block is formed into hexagonal nested cells, similar in appearance to a cross-section of a beehive. Support blocks 313 provide radial support to the rotor coils 304 when in operation.

In this embodiment, support plate 302 is incorporated as one of the laminations within rotor coil assembly 304 and occupies substantially the entire area bounded by the inner surface of the rotor assembly. Support plate 302 includes a central region having an aperture 316 through which a support post or key 318 of the rotor body extends. After support plate 302 is positioned over key 318, pole cap 320 is secured to the exposed upper end of key 318.

In certain applications and particularly for larger rotating machine embodiments, the temperature gradient can be sufficient to cause a relatively large change in the axial dimension of horizontal support 314. Although the change in dimension in the tangential direction is tolerable, the larger change of the axial dimension may cause the horizontal support to fracture. As will be described immediately below, other support arrangements may be more suitable for such large machine applications.

For example, referring to Figs. 18, 18A and 19, in another embodiment, three vertical support plates 402 are shown spaced along the major long axis of a racetrack-shaped rotor coil assembly 404 to support superconducting windings 401. Each of the vertical support plates 402 is formed of the same or similar rigid and thermally insulative material of horizontal support plate 302 shown in Fig. 16. In other embodiments, more than three vertical support plates can be used to support the superconducting windings.

Referring to Fig. 20, an inner spacer 409 and an outer spacer 412 are used to externally support the superconducting windings of rotor coil assembly 404.

During operation of the rotating machine, support plates 402 receive both radial forces and tangential torque (i.e., tangential to the plane of the support plates) generated by the rotor coil assembly. Included as part of the radial forces generated by the rotor coil assembly, are "ovalization" forces, which are caused by the racetrack-shaped, oval superconducting windings when, in operation, having a tendency to move the longer sides of the coil outward so that the coil assembly becomes more circular. A racetrack-shaped coil undergoing these ovalization forces is said to "go round."

Vertical support plates 402 receive the forces generated by the rotor coil assemblies and efficiently transfer the forces to the warm rotor body. In particular, each support plate 402 has ends that are adhesively bonded (e.g., epoxy) at an inner joint 405 of the surrounding rotor coil assembly. The center region of each support plate 402 is mechanically coupled to a portion of a warm rotor body 406 through a cylindrical joint 408 having a shape for effectively receiving and distributing the forces.

For example, referring to Fig. 21, each cylindrical joint 408 is in the form of two halves of a bifurcated post 410, each having a planar surface 411 bonded to opposing sides of vertical support plate 402 and a rounded surface 412 which contacts a correspondingly rounded and concave surface of the warm rotor body.

Referring to Fig. 22, because forces react in a direction normal to a contacting surface, the rounded surface of post 410 receive tangential forces F_t generated by the rotor coil assembly and conveyed through support plates 402. These tangential forces F_t are transferred from the bifurcated post to the warm rotor body at their interface in a radial direction. This radial force F_R can be resolved into a first component F_{T1} parallel with the tangential force F_t and a second component F_c transverse to the first component F_{T1}. The second component F_c represents a clamping force, which ensures a reliable mechanical connection between the rotor body and bifurcated post 410.

Multi-layer thermal insulation 416 is provided within spaces between the warm rotor body and vertical support plates 402 as well as between the rotor body and rotor coil assembly. The thickness of the thermal insulation is dependent on the size of the gap and can be as thick as one inch or larger. As was the case with the embodiment of Figs. 16 and 17, support blocks 413 are positioned about the periphery of the rotor coil and between the rotor coil and a pole cap 420.

With reference to Figs. 23, 24A, and 24B, another approach for supporting the rotor coil assemblies of the superconducting rotating machine is described. In the diagrammatic representation of the four-pole topology shown in Fig.23, an iron rotor body 500 includes four spaced poles 502a-502d, each supporting a superconducting rotor coil assembly. In particular, a first pair of diametrically opposing superconducting rotor coil assemblies 503, 504 is positioned along a first axis 506. A second pair of diametrically opposing pair of superconducting rotor coil assemblies 508, 510 is positioned along a second axis 512,

transverse to axis 506. The rotor coil assemblies are supported along the outer periphery of rotor body 500 at stepped profiles formed along axes 506, 512.

Each of rotor coil assemblies 503, 504, 508, 510 includes superconducting windings 509 positioned within a support structure 511. Support structure 511 is formed of a relatively rigid material having a thermal coefficient of expansion coefficient similar to that of the windings. In this embodiment, support structure 511 is formed of stainless steel and includes support plates 513, which extend between the superconducting windings 509. In embodiments in which the iron rotor body is "warm," (i.e., not at cryogenically-cooled temperatures), multi-layered insulation 515 (e.g., layers of aluminized mylar) is generally provided between the rotor coil assemblies and rotor body. This arrangement minimizes heat loss between the rotor body and cryogenically-cooled rotor assemblies. Between each of the adjacent rotor coil assemblies is a triangularly-shaped wedge 514 for supporting the coil assemblies. Each wedge is preferably formed of the material used to make support structure 511.

As shown most clearly in Fig. 24B, wedges 514 include two walls 525, each of which includes a hole for allowing a bolt 526 to pass there through to be received within threaded holes 528 of support structure 511. With this configuration, all coils with their support wedges form a self-supporting structure, without support from the "warm" iron rotor body 500.

Referring again to Fig. 23, pole caps 516a-516d are positioned over the rotor coil assemblies and respective ones of the iron pole 502a-502d. Pole caps 516A-516D are typically used to control field distributions at the stator winding.

The self-supporting wedge arrangement described above is also applicable to other multiple pole arrangements. For example, referring to Fig. 25, a superconducting rotor assembly 530 having an eight-pole topology is shown. Rotor assembly 530 includes a rotor body 531 having eight poles 532a-532h, each having a superconducting rotor assembly 534 mounted thereto. In this embodiment, each pole is equally spaced by 45 degrees around the periphery of a rotor body. As was the case described above in conjunction with Fig. 24, triangular wedges 536 are positioned between adjacent rotor coil assemblies 534.

The self-supporting wedge concept is applicable as well to air core rotating machines. As shown in Fig. 26, for example, a support structure 540 includes an outer wall 542 for

attachment to triangular-shaped wedges 544 (only one shown). Support structure 540 also includes extending support plates 546 which separate and support superconducting windings 548. The distal end of the support plates 546 and the superconducting windings define an open or clear air core 550 of a rotor assembly.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, the components described could be adapted to produce other superconducting rotating machines, such as a superconducting generator. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is: